Heavy Tau Neutrino as the Late Decaying Particle in the Cold Dark Matter Scenario

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Abstract

The tau neutrino with a mass of about 10 MeV can be the "late decaying particle" in the cold dark matter scenario for the formation of structure in the Universe. We show how this may be realized specifically in the recently proposed doublet Majoron model.

Study of the mass and interaction of neutrinos is a long-standing subject in particle physics and offers one of the key clues to possible new phenomena beyond the standard model. Majoron models have been attracting a lot of interest in this respect. They provide the neutrinos with Majorana masses and a new type of interaction not present in the standard model. The interaction is due to the coupling of the neutrinos and other matter to the Majoron, a Nambu-Goldstone boson associated with the violation of the lepton number symmetry. This extra interaction was originally used to facilitate the decay of a massive neutrino which would otherwise be ruled out due to the cosmological constraint on the neutrino mass [1]. In a different application, it allows a stable massive neutrino to be suitable as a dark matter candidate [2]. In this paper, we examine another possibility that this interaction may bring about; the τ neutrino (ν_τ) as a candidate for the late decaying particle in the cold dark matter (CDM) scenario for the formation of structure in the Universe [3, 4, 5].

The idea of the late decaying particle was proposed to reconcile a setback of the CDM model in explaining the formation of large-scale structure in the Universe [3, 4]. This setback became more evident by the recent COBE detection of anisotropy in the temperature of the cosmic background radiation: The theoretical prediction for an $\Omega = 1$ inflationary Universe on the power spectrum of the density fluctuation gives a larger power than the observation at small scales $\lambda \leq 10h^{-1}$ Mpc (the Hubble constant $H_0 = 100h$ km/s/Mpc) once it is normalized at large scales $\lambda \sim 10^3 h^{-1}$ Mpc using the COBE detection [6]. A remedy is to delay the time of matter-radiation equality, at which sub-horizon-sized fluctuations begin to grow. The delay reduces the power on the small scales, while the resulting larger horizon size means relatively more large-scale structure than the simple CDM scenario.

A massive particle species that decays into relativistic particles can do this trick. Since the decreasing rate of the relic energy density of massive matter is smaller than that of radiation, its energy necessarily dominates the Universe if it is sufficiently long-lived. Its

subsequent decay into relativistic particles gets the Universe into the radiation-dominant era again with more energy, and delays the time of forthcoming matter-radiation equality.

In the late decaying particle scenario, we have two matter-radiation equality epochs: first the relic ν_τ dominates the Universe and then the cold dark matter does. They are separated by a radiation-dominated era after the ν_τ-decay. We distinguish values of cosmological variables at these epochs with subscripts '$_{\rm EQ1}$' for the former and '$_{\rm EQ2}$' for the latter, e.g., the age of the Universe $t_{\rm EQ1}$, the temperature $T_{\rm EQ1}$, the horizon size $\lambda_{\rm EQ1}$, etc.

Recently, Dodelson et al. examined a scenario in which a massive τ neutrino, with its mass in a range $m_{\nu_\tau} \sim 1$ – 10 MeV, may be the late decaying particle [5]. (See also Ref. [7] for other candidates in particle physics models.) An important constraint for this scenario is the one from primordial nucleosynthesis: the equivalent number of massless neutrino species N_ν should be less than 3.3 [8] or 3.04 [9] but a τ neutrino of this mass range may possibly contribute more than this bound [10].

This difficulty is rather easily evaded in a Majoron model, thanks to the new interaction between ν_τ and the Majoron $\varphi_{\rm L}$. In the standard model, the relic abundance Y_∞ of ν_τ, the ratio of its number density to the entropy density (see [11] for the definition), is determined by the speed of the annihilation process via $\rm Z^0$ exchange compared to the Universe expansion [11, 12]. In Majoron models the process

$$\nu_\tau\, \nu_\tau \longrightarrow \varphi_{\rm L}\, \varphi_{\rm L}, \tag{1}$$

also works to decrease the relic abundance. The ν_τ– $\varphi_{\rm L}$ coupling is proportional to $m_{\nu_\tau}/v_{\rm L}$, where $v_{\rm L}$ is a scale for the lepton number violation. Thus the process (1) can be still active even after the $\rm Z^0$ exchange process shuts off if this m_{ν_τ} to $v_{\rm L}$ ratio is sufficiently large. Then the relic density can be much smaller than the one in the standard model. This can make ν_τ invisible with respect to the dynamical evolution of the Universe at the time of primordial nucleosynthesis and avoid the resulting constraint. In other words, the lifetime upper bound

of 100 seconds estimated for a heavy ν_τ to be the late decaying particle in Ref. [5] is no longer a constraint in this case.

The doublet Majoron (DM) model which we have proposed recently [13] is very suitable for the late decaying particle scenario. An advantage of this model, compared with the singlet Majoron model, is that it allows us to use a smaller scale $v_{\rm L}$ for the lepton number violation and thus a larger $\nu_\tau - \varphi_{\rm L}$ coupling without conflicting with the basic concept of the seesaw mechanism [14]. We estimate $T_{\rm EQ1}$ for various values of $v_{\rm L}$ and m_{ν_τ}, and show that it indeed provides a possibility that ν_τ can be the late decaying particle.

Let us first estimate how low the temperature $T_{\rm EQ1}$ should be in order to satisfy the constraint from primordial nucleosynthesis. The precise definition for $T_{\rm EQ1}$ is the temperature at which the τ neutrino energy $\rho_{\nu_\tau} = (2\pi^2/45) m_{\nu_\tau} Y_\infty \, g_{*S} \, T^3$ becomes the same as the radiation energy $\rho_{\rm R} = (\pi^2/30) g_* T^4$,

$$T_{\rm EQ1} = \frac{60}{45} \frac{g_{*S}}{g_*} m_{\nu_\tau} Y_\infty, \tag{2}$$

where g_* and g_{*S} are the statistical weights of the light degrees of freedom for the energy and entropy density, respectively. They are functions of temperature; specific values of g_* and g_{*S} at a given temperature depend on details of the thermal history of the Universe. The values we specifically use correspond to the following situation: ν_τ was so heavy, m_{ν_τ} $>$ a few MeV, that it was non-relativistic when the Z^0 exchange process for its annihilation shuts off; its abundance is frozen at the temperature $T_{\rm f}$, which is assumed to take place before electrons (e) and positrons (e^+) annihilate in pairs, i.e., $T_{\rm f} >$ a few tenths of MeV. Thus we use $g_* = g_{*S} = 10$ (a sum of contributions from photon (γ), e, e^+, $\nu_{\rm e}$, ν_μ, and $\varphi_{\rm L}$) for evaluating $T_{\rm f}$ and Y_∞. After the pair annihilation of e and e^+, they reduce to $g_* = 3.17$ and $g_{*S} = 3.64$. If ν_τ is relativistic at the termination of the Z^0 process, these values change. Also there may occur a deviation in the temperatures of γ and $\varphi_{\rm L}$. We, however, neglect these subtleties in this paper. For lighter neutrino, $m_{\nu_\tau} \sim 1$ MeV, this may cause an error;

but the numerical error in the final results of $T_{\rm EQ1}$ expected by this neglect is at most 30 – 40 % and does not affect the discussions we make in this paper.

The temperature at which primordial nucleosynthesis commences is about 1 MeV [11]. At this temperature, we need to satisfy the condition $g_* < 11.3$ or 10.82, which correspond to the bounds $N_\nu < 3.3$ [8] or 3.04 [9], respectively. Since $g_* = 10$ at $T \sim 1$ MeV, the ν_τ fraction in the energy density must satisfy

$$\frac{\rho_{\nu_\tau}}{\rho_{\rm R}} \leq 0.08. \tag{3}$$

On the other hand, the fraction in terms of $T_{\rm EQ1}$ is given by

$$\frac{\rho_{\nu_\tau}}{\rho_{\rm R}} \simeq \frac{g_{*S}(1\ {\rm MeV})}{g_*(1\ {\rm MeV})}\frac{g_*(T_{\rm EQ1})}{g_{*S}(T_{\rm EQ1})}\frac{T_{\rm EQ1}}{1\ {\rm MeV}} \sim \frac{T_{\rm EQ1}}{1\ {\rm MeV}} \tag{4}$$

as long as $T_{\rm f}$ is higher than 1 MeV. Thus a τ neutrino with $T_{\rm EQ1}$ less than 10^{-2} MeV is safe in this respect.

To evaluate Y_∞, we use formulas given by Kolb and Turner [11],

$$Y_\infty = \frac{3.79(n+1)x_{\rm f}^{n+1}}{(g_{*S}/{g_*}^{1/2})m_{\rm Pl}m_{\nu_\tau}\sigma_0}, \tag{5}$$

and

$$\begin{aligned} x_{\rm f} &= \ln[0.038(n+1)(g/{g_*}^{1/2})m_{\rm Pl}m_{\nu_\tau}\sigma_0] \\ &\quad -(n+1/2)\ln\{\ln[0.038(n+1)(g/{g_*}^{1/2})m_{\rm Pl}m_{\nu_\tau}\sigma_0]\}, \end{aligned} \tag{6}$$

where $m_{\rm Pl} = 1.2 \times 10^{19}$ GeV is the Planck mass, $g = 2$ for ν_τ, n and σ_0 are read off from the form of the thermally averaged cross section for the process

$$\langle \sigma v_{\rm rel} \rangle = \sigma_0 (T/m_{\nu_\tau})^n. \tag{7}$$

The freezing temperature is given by $T_{\rm f} \simeq m_{\nu_\tau} x_{\rm f}^{-1}$.

The evaluation of the cross section is straightforward. The appropriate interaction terms are given by

$$\begin{aligned}\mathcal{L} &= \frac{\partial^\mu \varphi_{\mathrm{L}}}{2v_{\mathrm{L}}}({\nu_\tau}^\dagger \bar{\sigma}_\mu \nu_\tau) + \frac{(\partial^\mu \varphi_{\mathrm{L}})\,(\partial_\mu \varphi_{\mathrm{L}})}{2v_{\mathrm{L}}}\,(\cos\alpha\,\phi_- + \sin\alpha\,\phi_+) \\ &\quad + \frac{m_{\nu_\tau}}{2v_{\mathrm{L}}}\,(\cos\alpha\,\phi_- + \sin\alpha\,\phi_+)\left\{\left({\nu_\tau}^{\mathrm{T}} i\sigma^2 \nu_\tau\right) - \left({\nu_\tau}^\dagger i\sigma^2 {\nu_\tau}^*\right)\right\},\end{aligned} \tag{8}$$

where $\phi_\pm$ are neutral scalar fields, α and β are mixing angles, which are the same as those defined in Ref. [13]. The corresponding cross section in the singlet Majoron model has been evaluated in Refs. [15]. We calculate the same Feynman diagrams as those in [15]: two diagrams with the $\nu_\tau - \varphi_{\mathrm{L}}$ vertices and two scalar-exchange diagrams. The freezing of the abundance mostly takes place when the initial two ν_τ's are non-relativistic and their energy is much smaller than the mass of $\phi_\pm$. In this energy region, the $\phi_\pm$-exchange diagrams are negligible and we obtain the same result as the one in Ref. [15],

$$\sigma = \frac{1}{96\pi}\frac{{m_{\nu_\tau}}^2}{{v_{\mathrm{L}}}^4}\frac{|\vec{p}\,|}{E} \tag{9}$$

in terms of the energy E and the momentum $\vec{p}$ of one of the initial neutrinos in the center of mass frame. A characteristic behavior of σ, *i.e.* it vanishes at vanishing $|\vec{p}\,|$, comes from a combined effect of the statistics of identical particles and the conservation of both angular momentum and "CP"; the latter can be defined as a discrete symmetry of the $\nu_\tau - \varphi_{\mathrm{L}}$ interaction and forbids the s-wave contribution. The thermally averaged cross section is given by the integration over the distribution function for the relative velocity $v_{\mathrm{rel}} = 2|\vec{p}\,|/E$[1],

$$\begin{aligned}\langle \sigma v_{\mathrm{rel}} \rangle &\equiv \int d^3 v_{\mathrm{rel}} \left(\frac{m_{\nu_\tau}}{4\pi T}\right)^{3/2} e^{-m_{\nu_\tau} v_{\mathrm{rel}}^2/4T}\,\sigma v_{\mathrm{rel}} \\ &= \frac{1}{32\pi}\frac{m_{\nu_\tau} T}{{v_{\mathrm{L}}}^4}.\end{aligned} \tag{10}$$

This result gives $\sigma_0 = (1/32\pi)({m_{\nu_\tau}}^2/{v_{\mathrm{L}}}^4)$ and $n = 1$ in (7).

[1] Note that the initial neutrinos in the process (1) are identical Majorana particles. Thus the event rate of the process per unit comoving volume is (1/2) of $\langle \sigma v_{\mathrm{rel}} \rangle$ defined this way. In the Boltzman equation, which is the basis to derive the formulas (5)-(6) [11], this factor 1/2 is cancelled by another factor 2 that represents the fact that two neutrinos annihilate in the process.

We plot the values of $T_{\rm EQ1}$ obtained by Eqs. (2), (5), and (6) for various values of $v_{\rm L}$ and m_{ν_τ} as contours in Fig. 1. The thermal history of the Universe we have assumed based on the DM model is correct for most of the range of values of m_{ν_τ} and $v_{\rm L}$ shown in Fig. 1. Obviously $T_{\rm EQ1}$ needs to be higher than $T_{\rm EQ2}$, which is about 1 eV, in order that ν_τ plays the role of the late decaying particle. Thus the parameter region in Fig. 1 for accommodating the late decaying particle is

$$-9 < \log\left(\frac{T_{\rm EQ1}}{1\ {\rm GeV}}\right) \leq -5. \tag{11}$$

(Note that ν_τ with $T_{\rm EQ1}$ less than 1 eV can be a candidate of dark matter [2].)

In the DM model, $v_{\rm L}$ smaller than 10 GeV predicts a light scalar boson ϕ_-, which can be a rare decay product in $\mathrm{Z}^0 \to \phi_- +$ (a fermion pair), and contradicts the known lower mass bound, about 60 GeV, for the standard Higgs boson [13][2]. Thus a region $v_{\rm L} \geq 10$ GeV is left for the τ neutrino to be the late decaying particle. The temperature $T_{\rm EQ1}$ is, then, 1 – 10 keV.

The lifetime of the τ neutrino, τ_{ν_τ}, should be adjusted so that it generates an appropriate amount of radiation energy in its decay. Let us estimate the required lifetime. We use the sudden-decay approximation and assume ν_τ decays all at once at the age $t_{\rm D} \simeq \tau_{\nu_\tau}$ and temperate $T_{\rm D}$. The total radiation energy density after the decay, including the decay product R′, is

$$\rho_{\rm R+R'} = \frac{\pi^2}{30} g_* T^4 \left(1 + \frac{T_{\rm EQ1}}{T_{\rm D}}\right). \tag{12}$$

To fit the predicted power spectrum of the density fluctuation to the observation, this needs to be about 3 times bigger than the radiation energy in the standard prediction [5]. Thus $T_{\rm EQ1}/T_{\rm D} \simeq 2$. Taking into account the relation $T \propto t^{-2/3}$ in the ν_τ-dominated era, we get

[2]Since ϕ_-–Z^0–Z^0coupling is proportional to $(-\cos\beta\sin\alpha + \sin\beta\cos\alpha)$, we can fix this problem by tuning the two mixing parameters in the model, i.e., $\alpha \simeq \beta$; but we will not pursue it in this paper.

$\tau_{\nu_\tau} \simeq 3\, t_{\rm EQ1}$. Since the age at $T_{\rm EQ1}$ is

$$t_{\rm EQ1} \simeq 2.4 \times 10^{19} \left(\frac{T_0}{T_{\rm EQ1}} \right)^2 \ \text{sec}, \tag{13}$$

where $T_0 = 2.735K$ is the present (photon) temperature of the Universe, $\tau_{\nu_\tau}$is 10^4 – 10^6 seconds. The lifetime in the DM model is given by [13]

$$\tau_{\nu_\tau}{}^{-1} = \frac{1}{64\pi} |R_{\nu_\tau \nu_a}|^2 \frac{m_{\nu_\tau}{}^3}{v_{\rm L}{}^2}, \tag{14}$$

where $R_{\nu_\tau \nu_a}$ is the flavor changing matrix element between ν_τ and lighter neutrinos ($\nu_a = \nu_{\rm e}, \nu_\mu$). If we take $v_{\rm L} \simeq 20$ GeV and $m_{\nu_\tau} \simeq 10$ MeV to get an idea of the magnitude of $|R|$, it resides in a range $|R| \sim 10^{-9}$ – 10^{-10}. The smallness of these values can be regarded as a result of the seesaw mechanism: $|R|$ can be parametrized as $[(m_{\nu_\tau}/M) \sin\theta]$ with M the mass scale of the gauge singlet neutrino and θ a mixing angle; the values we used for m_{ν_τ} and $v_{\rm L}$ imply $M \sim 10$ TeV and $|R| \sim 10^{-6}\, \theta$.

In a late-decaying-particle scenario for structure formation, we necessarily have an extra small scale corresponding to the horizon at $t_{\rm EQ1}$. Its size $\lambda_{\rm EQ1}$ at $T_{\rm EQ1}$, after being scaled up to the present taking into account the expansion of the Universe, is

$$\lambda_{\rm EQ1} \simeq 4.8 \times 10^5 \left(\frac{T_0}{T_{\rm EQ1}} \right) \ \text{Mpc}. \tag{15}$$

Thus $\lambda_{\rm EQ1} \simeq 10 - 100$ kpc for the allowed parameters in the DM model. The consequence of the existence of this scale for structures in the Universe needs to be clarifed by further investigations. It may be related to the dwarf galaxies [3].

In summary, we have shown that the DM model represents an appropriate particle physics model for realizing a possibility that the τ neutrino, with a mass of about 10 MeV and a lifetime in the range 10^4 to 10^6 seconds, is the late decaying particle in the CDM scenario for the formation of structure in the Universe.

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Figure caption

Fig. 1 Contour plot of $\log[T_{\rm EQ1}/1{\rm GeV}]$. The contours correspond to $\log[T_{\rm EQ1}/1{\rm GeV}] = -5, -6, -7, -8, -9, -10$ from top to bottom.